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AUTHOR McConkie, George W.; Currie, Christopher B.
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ABSTRACT

A study explored the phenomenon of space constancy or visual stability of stimulus patterns across saccades (a series of small jerky movements of the eye) by making changes in natural, full-color pictures during selected saccades as observers (18 members of the University of Illinois community) examined them for 20 seconds in preparation for a recognition test. In the first experiment, the pictures were displaced up, down, left, or right by 0.3, 0.6, or 1.2 degrees. In the second experiment, the pictures were expanded or contracted in size by 10% or 20%. As a secondary task, subjects pressed a button whenever they detected a change in the picture. Three results from previous studies with simpler stimuli did not generalize to this situation. Evidence suggests that subjects' detection of image displacements as they examine complex pictures primarily involves the use of local information in the region of the saccade's landing position. Findings suggest support for a saccade target theory, which postulates that a shift of the stimulus is detected on the basis of the post-saccadic retinal location of the object to which the eyes are sent. Further research is needed to identify other sources of evidence for instability in the stimulus configuration from one fixation to the next. (Contains 42 references, 3 notes, 5 tables of data, and 4 figures of data.) (Author/RS)

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174 Children's Research Center
51 Gerty Drive
Champaign, Illinois 61820

MANAGING EDITOR
Technical Reports
Fran Lehr

MANUSCRIPT PRODUCTION ASSISTANT
Delores Plowman

Abstract

As people visually examine their world, the proximal stimulus pattern changes position on their retinae with every saccade, but they still perceive the world as being stable. This phenomenon of space constancy or visual stability was explored by making changes in natural, full-color pictures during selected saccades as observers examined them for 20 s in preparation for a recognition test. In Experiment 1, the pictures were displaced up, down, left, or right by 0.3, 0.6, or 1.2 deg. In Experiment 2, the pictures were expanded or contracted in size by 10% or 20%. As a secondary task, subjects pressed a button whenever they detected a change in the picture. Three results from previous studies with simpler stimuli did not generalize to this situation. Evidence suggests that subjects' detection of image displacements as they examine complex pictures primarily involves the use of local information in the region of the saccade's landing position. A saccade target theory of visual stability is proposed.

VISUAL STABILITY ACROSS SACCADES WHILE VIEWING COMPLEX PICTURES

Making a saccadic eye movement causes a displacement of the light pattern across the retinae. If a similar retinal displacement occurs during an eye fixation, there is perception of movement: that is, the world appears to jump. However, the same pattern of motion on the retinae, occurring as a consequence of making a saccade, is not perceived and the world appears stable.[1] This phenomenon, referred to traditionally as *space constancy*, and which we will call *visual stability*, permits people to visually explore the world with a moving sensory matrix without mis-attributing self-induced stimulus motion on the matrix to the world itself. How the visual system achieves this stability has been a matter of speculation and research since Helmholtz (1866/1963) discussed the problem.

Two classes of theories have been proposed to explain this visual stability. One class of theories assumes that the characteristics of the proximal stimulus alone are sufficient to distinguish between retinal change resulting from saccadic eye movements and change resulting from movement in the world. The other class of theories assumes that some additional, non-retinal information is required, though individual theories differ in the nature of the information proposed.

Proximal Stimulus Alone: Gibson

Gibson (1966) argued that the transformation of the visual array over time that results from making a saccade is different from that which typically results from motion in the world. A saccadic eye movement produces a rigid displacement of the entire light pattern on the retinae. Thus, this type of transformation specifies a self-induced stimulus displacement rather than a change in the world. Furthermore, though not stated by Gibson, saccadic suppression (Volkman, Schick, & Riggs, 1968), together with visual masking from pre- and post-saccadic visual fields, prevents the perception of the stimulus motion on the retinae that results from a saccade-produced stimulus displacement. Thus, a rigid stimulus transformation, together with no direct sensation of the motion that typically accompanies stimulus transformations, affords the perception of a stable world.

Two types of evidence argue against Gibson's explanation. First, as MacKay (1973) and Bridgeman (1981) point out, pressing the side of the eyeball while fixating a constant position produces a perception of world motion even when the light pattern remains stable on the retina. Second, if the stimulus is physically displaced during a saccade this can be detected (Bridgeman, Hendry, & Stark, 1975) even though the stimulus change consists of a rigid transformation during a saccade. These two observations indicate that the experience of world motion can arise without stimulus transformation on the retina, and in spite of a rigid transformation. Thus, additional information is required in distinguishing between world- and self-motion.

Theories Postulating a Secondary Factor

There are currently three classes of theories that postulate the use of something else beyond the transformation of the retinal stimulus pattern itself in achieving the perception of a stable visual world as saccades are made. They will be referred to as cancellation theories, "taking-into-account" theories, and target object theories.

Cancellation Theories

Von Holst and Mittelstaedt (1950/1971) proposed that when the visual system produces a neural signal to cause a saccadic eye movement, an efference copy is also generated that is used to cancel the resulting retinal displacement. This efference copy, or corollary discharge, is strictly correlated with the original signal. The retinal image, or afferent signal, is retinally displaced by a distance equal to that

of the saccade, but in the opposite direction. Thus, by combining the efference copy and the post-saccadic afferent signal, the saccade-produced displacement is cancelled and is not perceived.

Breitmeyer, Kropfl, and Julesz (1982) suggested further detail for such a mechanism, resulting in an integration, or spatiotopic fusion, of the successive images. Their proposed mechanism would operate early in vision to eliminate the retinal displacement produced by a saccade, thus yielding a stable, continuous internal signal from which continuous vision proceeds.

Cancellation theories predict that a mismatch between the efference copy and the afferent signal will be attributed to movement in the world. Such mismatches can be produced by physically moving the stimulus during saccades, so its position in the world is different following the saccade than it was prior to the saccade. Extensive psychophysical research has been conducted to examine the sensitivity of the visual system to these types of intra-saccadic stimulus displacements, as a way of studying the mechanism underlying space constancy. Most of this research has been conducted in complete darkness with stimuli consisting of dots or simple light patterns that are displaced different distances and directions during saccades. The subjects' task is to detect the stimulus displacements when they occur. The primary findings from these studies can be summarized as follows:

Saccade length function: If the stimulus shift magnitude is held constant, displacement detection drops as saccade length increases (Bridgeman et al., 1975; Li & Matin, 1990; Mack, 1970).

Displacement threshold level: Displacements can be reliably detected when the magnitude of the shift is about 10% to 20% of the length of the saccade (Mack, 1970; Whipple & Wallach, 1978).

Constant detection/saccade length ratio: A constant detection level is maintained as saccade length increases if the magnitude of the stimulus displacement is a constant proportion of the saccade length (Li & Matin, 1990).

Direction independence: Detection likelihood is independent of relative saccade direction, where this is defined as the angle between the saccade and stimulus shift vectors (Mack, 1970; Bridgeman et al., 1975). One exception to this is reported by Macknik, Fisher, and Bridgeman (1991).

The typical interpretation of the above findings is that the extraretinal information concerning eye position is somewhat imprecise, and that this imprecision increases with saccade length (Li & Matin, 1990). Skavenski (1990) suggests that there is a need for some mechanism to determine how much of the mismatch between efference copy and afferent signal is to be attributed to error in the system and how much is due to movement in the world.

Recent physiological research by Duhamel, Colby, and Goldberg (1992) provides support for the existence of a remapping of retinal space with each saccade, as cancellation theory suggests. However, two lines of research have raised questions about cancellation theories. First, Matin (1986) has attempted to measure the accuracy of the extraretinal in formation concerning eye position that is produced in making a saccade, and has concluded that the accuracy is too low to account for research results on visual stability. Second, a number of studies have failed to find evidence for the integration or spatiotopic fusion of images from successive eye fixations that cancellation theories suggest (for a review, see Irwin, 1992).

Finally, it appears that even if the cancellation mechanism is the basis for visual stability when examining simple stimuli in the dark, its role may be severely reduced when viewing more complex stimuli. Matin, Picoult, Stevens, Edwards, and MacArthur (1982) studied perception in subjects with partially paralyzed oculomotor muscles. In this condition, it was assumed that attempting to make a saccade produced a large deviation between the efferent signal, indicating the intended length of the saccade, and the afferent signal, indicating where the eyes actually positioned themselves. When subjects were asked, in

the dark, to saccade away from illuminated points set directly ahead at eye level, they perceived the points of light to move even though they did not. This illusion of stimulus movement was attributed to the mismatch between efferent and afferent signals. However, when the same task was performed in a normally illuminated room, no motion was perceived. Stark and Bridgeman (1983) obtained compatible results with another method. If the results of studies investigating intrasaccadic displacements of simple stimuli in the dark do not generalize to more normal viewing situations, this calls into question the assumption that the mechanism being studied underlies visual stability. A primary goal of the experiments presented below was to determine whether these results do generalize to the viewing of complex pictures in a natural perceptual task.

Taking-into-account theories: A second class of theories also postulates the existence of retinal and extra-retinal signals but without assuming a cancellation or remapping process. MacKay (1973) assumes the existence of a spatiotopic map, and argues that the efferent command to make a saccade is also a signal to the visual system to begin evaluating the retinal signal for "map-changing information-content" (p. 314). If the retinal signal contains information that the world has changed, and the evaluation mechanism detects this, then the system decides that the world is different from the internal map, and proceeds to update that map. Furthermore, the evaluation mechanism must decide, by some criteria, whether or not the retinal image displacement "is significantly different from that which the saccade was calculated to bring about" (p. 318). MacKay does not propose the exact mechanism by which this evaluation is carried out, and leaves open the possibility that it is flexible and varies under different conditions. However, it seems that it must involve a comparison of the retinal stimulus pattern with information retained from prior fixations, together with some basis for judging whether the stimulus pattern is where it is expected to be. The latter judgment could involve an efference copy, as with cancellation theory. However, in MacKay's theory, the efference copy would simply be "taken into account" (Bridgeman, van der Heijden, & Velichkovsky, 1994) in judging whether the world has changed, rather than being the basis for a cancellation process.

Bridgeman et al. (1994) abandon the use of an efference copy in achieving visual stability, and deny that any type of perceptual instability is produced by the displacement of the retinal signal across saccades. They argue that while it is true that a displaced pattern on the retina is reflected by a change in position of the retinal pattern in the various cortical retinotopic maps (e.g., the LGN, V1, V2, etc.), the position of any cortical pattern in a map is itself not a code for position. Rather, it is the particular pattern itself that is a code for position, and this pattern of activation is invariant across eye movements. (For neurophysiological and modeling evidence on this point, see Andersen, Essick, & Siegel, 1985, and Zipser & Andersen, 1988).

While Bridgeman et al.'s position explains the existence of space constancy, it raises the question of how the visual system detects rigid stimulus displacements across saccades. To deal with this problem, Bridgeman et al. (1994) postulate a mechanism that derives anew, with each fixation, the visual direction of the world from both extra-retinal (i.e., efferent and proprioceptive) and retinal sources of information. A comparison process across eye movements then detects any change in direction. This comparison process tolerates mismatches up to a point; beyond this point, the mismatch produces a perception of stimulus displacement.

In contrast to cancellation theories, which assume that a low-level visual process automatically cancels out the stimulus displacement by remapping retinal space, MacKay (1973) and Bridgeman et al. (1994) presume the existence of higher level mechanisms that are able to detect and make use of cues indicating that a stimulus change has occurred. If no such cues are detected, then space constancy is experienced. The use of available cues, including the weighting of retinal and extra-retinal information in detecting stimulus displacements, is likely to depend on characteristics of the visual stimulus, the task and the observers. Such flexibility would limit the generalizability of the psychophysical results from early studies of detectability (Mack, 1970; Bridgeman et al., 1975; Stark, Kong, Schwartz, Hendry, & Bridgeman, 1976; Whipple & Wallach, 1978). However, there are no published studies that report

psychophysical functions for detection rates of stimulus displacements with complex stimuli in more naturalistic tasks, in order to determine whether the earlier results generalize well to other conditions.

Target-object theories. A third type of theory is suggested in a "localist" or "retinotopic error" explanation that Bridgeman and Stark (1979) give to results obtained by Whipple and Wallach (1978), though they do not develop the theory further. Whipple and Wallach asked subjects to saccade between two sides of a large circle, 7 deg in diameter, and they shifted the circle different distances horizontally or vertically during the saccades. The ratio of the displacement size to the saccade length is called the "displacement ratio." The displacement was either parallel to the direction of the saccade, or was orthogonal to it. Whipple and Wallach discovered that displacements in the orthogonal direction must be twice as great as displacements in the parallel direction to produce equal detection frequency. Furthermore, the displacement ratio necessary for orthogonal displacements to be detected was much greater than that observed by other investigators (Mack, 1970; Bridgeman et al., 1975; Stark et al., 1976).

Bridgeman and Stark (1979) observed that, because the stimulus was a circle, the distance that the eyes landed from the edge of the circle was much greater when a parallel displacement occurred than when an orthogonal displacement occurred. Therefore, they reanalyzed the data using the distance of the eyes from their target, the edge of the circle (operationalized as the distance to the nearest point of the circle), as a predictor of detection frequency, rather than the displacement distance itself. Using this local information as a predictor eliminated the difference between parallel and orthogonal displacements, and brought the detection thresholds for orthogonal displacements into line with those obtained for other conditions, as well as with results from previous studies.

Bridgeman and Stark's observation suggests that the critical variable in detecting displacements could be the distance of the eye from its target at the beginning of the new eye fixation. In most research, this variable has been largely confounded with the size of the displacement itself: larger displacements take the eyes farther from their target. A target-object theory, then, would propose that the detection of displacements is based, not on an efference copy of the saccade signal, nor on global properties of the visual stimulus itself, such as general stimulus direction, but strictly on local information; for example, the distance of the intended target, at the beginning of the new fixation, from some anticipated retinal location, probably the center of vision.

The above review of the literature highlights two issues to be addressed in the studies described below: (a) do the psychophysical functions of intra-saccadic displacement detection that have been obtained in studies with simple stimuli presented in the dark generalize to the more normal condition of viewing complex, naturalistic stimuli, and (b) is the detection of such displacements based in some way on the global retinal pattern, or only on local aspects of the pattern in the region of the object to which the eyes were being sent?

Two experiments are reported below, in which subjects were asked to examine colored photographs of houses in natural settings in preparation for a recognition test. During selected saccades in the viewing, pictures were horizontally or vertically displaced (Experiment 1), or were increased or decreased in size (Experiment 2). As a secondary task, subjects were asked to press a button when they detected any type of change in the picture. Actually, the data for both studies were collected simultaneously, from the same subjects viewing the same pictures. Mathematical modelling of the data is used to address the two issues mentioned above. It should be noted that the experiments were not designed to investigate maximal detection under conditions optimized for that purpose. Rather, they were designed to provide information on the degree to which certain display changes, that are assumed in cancellation theory to interfere with the processes underlying space constancy, disrupt processing in a natural ongoing perceptual task to the extent that people notice, or detect, the disruption.

EXPERIMENT 1

The first experiment was conducted to examine the functional relationships between several variables and the likelihood of detecting an intra-saccadic displacement of a complex picture.

Method

Stimuli

Forty pictures of houses were digitized from photographs at 617 x 398 pixels with 16 bits of color per pixel. At a viewing distance of 27 inches, each image subtended an area of 22 x 15 deg.

Apparatus

The pictures were displayed on a Princeton Ultra-Synch monitor in 756 x 486 pixel mode, controlled by an ATVista display controller card in a 386 computer and refreshed at 60 Hz. To hide the edge of the display screen, the plastic molding of the monitor was blackened and a large (44 x 39 deg) glare filter was placed in front. This effectively hid the edge of the display screen and of the monitor itself, causing the pictures to appear on a large, darkened field.

In the ATVista display controller, four images can be stored in the image memory. This makes it possible to quickly switch from one image to another, simply by switching to a different region in image memory. This change can occur at the end of any horizontal scan, so the change can be initiated at any point during a vertical refresh of the image, and is completed in 16.7 ms.

The observer's eyes were tracked with a fifth-generation Dual Purkinje Image Eyetracker, sampling eye position every msec and producing 12-bit data values for horizontal and vertical position. The equipment was adjusted so that a 1 deg movement produced about a 200 value change in the eyetrack signal. Occasionally, successive samples differed by as much as 5 values, suggesting a noise level of about +/- 1 min of arc. Saccades were identified within 10 ms of their initiation, and on critical saccades an image change was initiated immediately upon detection. Saccade onset was detected online as a difference of 10 values or more (3 min of arc) between the current sample and that taken 4 ms earlier, followed by 4 additional samples indicating movement in the same direction. Because image changes can begin at any point during a vertical refresh cycle, the display of the old image was discontinued by no more than 10 ms after the onset of the saccade, and the new image was completely written on the monitor 16.7 ms later.

Subjects

Subjects were 18 members of the University of Illinois community who were paid to participate.

Task

Subjects examined the set of 40 pictures twice, the first time to study the pictures, and second time to indicate whether each picture was the same as one seen on the first viewing. Each picture was shown for 20 s on each presentation. As a secondary task, subjects were told to press a button immediately if they detected any change take place in a picture. During 4 warm-up pictures, they were shown the types of display changes that could occur. They were not told the frequency with which changes would occur.

Three types of changes occurred during the presentation of 32 of the pictures: horizontal or vertical displacements, changes in the size of the picture, and appearance or disappearance of an object for a

single fixation. Data from the last type of change are not reported in this paper. The display changes were made possible by storing four variations of a picture in the image memory: (1) the base image, (2) the same base image displaced horizontally or vertically from its original location, (3) an enlarged or reduced version of the base image, and (4) a version of the base image with an added or deleted object. Picture changes then occurred by switching among the four images. Subjects were not asked to discriminate among the different types of changes, but simply to indicate when any change was detected.

During the second viewing of the pictures, the only pictures that were different from the first viewing were 8 in which no display changes occurred during the viewing. The modifications to these pictures included left-right picture reversal or large object removal. Subjects indicated whether each picture was the same as one in the earlier viewing, following its 20 s viewing period.

Stimulus Displacement Conditions

The stimulus displacements used in this experiment included horizontal shifts of the entire image by 1.2 or 0.6 deg, either left or right, and vertical shifts of 0.6 or 0.3 deg either up or down. The choice of shift sizes was made on the basis of pilot data, indicating a wide range of detection frequencies, and in anticipation of analyses planned for Experiment 2.

Design

Of the 40 pictures, 8 were shown with no display changes, thus serving as a control condition. During the viewing of the other 32 pictures, the image was displaced on the screen on either the 2nd, 9th, 16th, 23rd or 30th saccade (in some cases, for reasons unrelated to the present study, a displacement scheduled later than the 2nd saccade was delayed by one saccade). A second displacement then occurred exactly 7 saccades later, bringing the picture back to its original position. Thus, during the viewing of each experimental picture, there were exactly two image displacements, except in cases where too few saccades were made to reach a critical saccade on which a displacement was planned. The 7-saccade difference between display changes was selected on the basis of pilot data that indicated subjects very seldom pressed their button in response to a stimulus change later than 7 saccades following the change. Typically, the response was within 2 or 3 saccades of the one on which the change occurred.

During another of the critical saccades, no display change occurred, thus providing a second control condition. Finally, during the remaining critical saccades, the other types of changes in the display occurred, as described above.

The order of the different types of display changes (displacement, size change, object appearance/disappearance, and no change) varied from picture to picture and was balanced insofar as possible. Furthermore, subjects were assigned to one of four groups, with groups differing in the order in which they saw the pictures, the order of the conditions on each picture, and the particular value of a condition for a given picture. Thus, if a picture were shifted upward by 0.6 deg for one group on the 2nd saccade, this same condition occurred for different pictures on other critical saccades for the other groups. Type of change and order of change were completely counterbalanced within each group. An example of the occurrence of the different conditions during the viewing of a single picture is shown in Figure 1.

[Insert Figure 1 about here.]

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Phosphor Persistence Concerns

Phosphor persistence is a concern in this study. If phosphor decays slowly enough, a change in the stimulus during a saccade can be detected on the basis of seeing the persistence during the following fixation. To determine whether this could be the basis for detecting changes in the current study, a follow-up experiment was conducted using a "shutter test" (Irwin, 1994). Four subjects viewed 6 of the images used in Experiment 1 monocularly through a shuttered aperature, controlled by computer, with viewing distance and lighting conditions similar to Experiment 1.

The shutter opened with a delay of 2 ms and remained open for 100 ms. The viewed image shifted horizontally or vertically by the same distances as the maximum shifts used in Experiment 1. The time of the shift varied with respect to the opening of the shutter: the shift occurred 30 ms after the opening of the shutter (condition 30), at the time of the opening of the shutter (condition 0) or 10, 20 or 30 ms prior to the opening of the shutter (conditions -10, -20, and -30).

Each subject had 96 trials in each shift condition, randomly mixed with 360 trials in a no shift control condition. On each trial subjects indicated whether or not they detected a change, and were encouraged to use a liberal criterion. In the control condition, detection (false alarm) likelihood was .26 across subjects. For the other conditions, detection rates were: .99, .36, .30, .27 and .24 for conditions 30, 0, -10, -20 and -30. Thus, changes made while the shutter was open were highly detectable. In the other conditions, the standard error used for comparisons with the control condition ranged from .025 to .026. Condition 0 differed from the control condition by more than twice the standard error. No other condition approached this criterion.

These results show that persistence is rarely, if ever, detected at or beyond 12 msec (i.e., 10 ms plus 2 ms shutter delay) following the initiation of a display change, thus being within the period of even short saccades.

Results

Each shift condition did not occur equally often for three reasons: sometimes a subject made insufficient saccades on a picture to cause all scheduled display changes to occur, sometimes data were lost due to blinks and eyetracking difficulties, and sometimes the last critical saccade was not followed by at least 7 fixations, in which case the data for that display change was not included because there may not have been adequate time for the subject to respond. Out of a possible 2,304 planned image displacements (18 subjects by 32 pictures by 2 displacements per picture), good data were obtained for 1,490.

False Alarms and Late Responses

In this study, positive responses could include two types of errors: false alarms, and late responses (responses to one display change that actually occurred after the next display change occurred). The frequency of these can be estimated using data from the two control conditions included in the study.

The frequency of false alarms was estimated using data from control pictures in which no display changes occurred. The saccades on these pictures that corresponded to the critical saccades in the experimental pictures were identified, and the frequency of pressing the button during the following 7 fixations was calculated. This gave the frequency of responding during this interval when no display change occurred. The response rate was 0.6%.

A second estimate was made by calculating the frequency of responding to the control condition (no display change) on experimental pictures when that condition occurred on the 2nd saccade. In this case,

there were no preceding display changes on that picture to which the subject might be giving a late response. The frequency of responding was quite similar, 1.0%.

In cases in which the control condition occurred later than the 2nd saccade, it was always preceded by a display change seven saccades earlier. In these cases, it is possible that the response to the earlier change was late enough to occur following the critical saccade for the control condition. Therefore, the frequency of responding during the interval following the control condition in these cases gives an indication of the frequency of late responses plus false alarms. This frequency was 1%, which is low enough to allow false alarms and late responses to be ignored in the remaining analyses.

Saccade Length Function

The major goal of the Experiment 1 was to determine whether certain relations among saccade length, shift size, and shift detection, observed in prior studies, hold true while viewing complex pictures. To accomplish this goal, it was necessary to quantify the relations among these variables. The first step in doing this was to establish the relationship between saccade length and shift detection. The data were reduced to a list of cases, each consisting of a dyad: the length of the saccade during which the picture was shifted and whether or not the shift was detected. Thus, data were collapsed across subjects and shift size. The cases were sorted by the length of the saccade. Because the dependent variable was binary (detect or no detect), the relationship between saccade length and detection likelihood was plotted using a sliding window technique. A window was defined on the sorted data that included the shortest 100 saccades, and for these cases a detection likelihood and a mean saccade length were calculated. The window was then stepped in increments of 50 saccades, and at each new position, a detection likelihood and mean saccade length were obtained for the 100 cases contained within the window. Figure 2 shows the relation between these two variables, indicating that detection likelihood drops in a negatively accelerated manner as saccade length increases. The data are well fit by the function:

$$f(s) = A * e^{(K * s)} \quad (1)$$

where $f(s)$ is the likelihood of detection, A is a parameter indicating the intercept of the function, K is a parameter controlling the rate of change, and s is the saccade length.

[Insert Figure 2 about here.]

Non-linear regression was used to obtain maximum likelihood estimates for the parameters A and K, using the Nonlin module of SYSTAT (Wilkinson, 1989). This was done by minimizing the sum of the values obtained by taking the negative of the log of the difference between the model's prediction for each individual data point and the obtained binary data value (i.e., detection or non-detection on that trial), the negative log-likelihood difference. Because the data set was larger than SYSTAT could handle, the 151 longest saccades were removed from the data set, which consisted of all saccades over 7.25 deg. These cases showed a 2% detection rate, and would play little role in the ultimate fit of the model. The remaining 1,339 cases yielded estimates of .863 for A, the intercept parameter, and -.591 for K, the slope parameter, with a loss value of 619.642, shown as Model A in Table 1. A graph of equation (1) with these parameter values is included with the windowed data in Figure 2. It should be noted that the model-fitting process was carried out using data for individual saccades, and not using the "binned" data from which Figure 2 was constructed. Thus, the figure provides only an approximate indication of the actual fit, which cannot be presented graphically.

[Insert Table 1 about here.]

Goodness of fit was tested with a chi-square test. Doubling the negative log likelihood loss value yields an index that is chi-square distributed. By this test, the obtained loss value is not statistically significant [X^2 (1337, N = 1339) = 1239.484, p = .977]. Thus, the data do not deviate significantly from the model's predictions. In fact, only one of the models presented below is statistically rejected by this test, so the results of this test are not reported further unless noted.

The excellent fit of equation (1) replicates and quantifies the saccade length function obtained in earlier studies, as described above.

Experiment 1 used 4 groups of subjects, and each group saw the entire set of stimulus pictures twice. Crossing these two variables, labeled "group" and "view," yields 8 conditions. To determine whether these variables influence detection rate, Equation (1) was fit to the data from each of these conditions separately, and the resulting 8 loss values were summed. This is the equivalent to fitting a 16-parameter model (i.e, 8 A and 8 K parameters) to the entire data set, with parameters varying with group and view variables. In cases where the value of A exceeded 1.0, a cap of 1.0 was placed on the value of that parameter in calculating the loss value. Thus, even when the intercept parameter was greater than 1.0, the model's prediction for the likelihood of detection at any point was constrained to lie between 1.0 and 0. This is equivalent to assuming that the observer's internal signal for stimulus movement may exceed 1.0, but when this occurs the resulting response rate can not exceed 100%. This constraint was used in all model-fitting in both Experiments 1 and 2. The total loss value for this 16-parameter model, labelled Model A´ in Table 1, was 611.365.

A chi-square test was used to test the null hypothesis that Model A´ fits the data no better than the original 2-parameter Model A. Model A´ was considered to be a "full" model, and Model A to be a reduced version of that model in which certain parameters from the full model have been dropped. Under these conditions, the difference between the loss value of the full model, which will never be less than that of the reduced model, and the loss value for the reduced model is chi square distributed with degrees of freedom being equal to the difference between the number of parameters of the two models. This test [X^2 (14, N = 1339) = 16.754, p = .73] did not find the difference to be statistically significant. The A parameters had a mean of 0.844 and SD of 0.148; the K parameters, -0.622 and 0.104. Thus, adding the 14 extra parameters failed to significantly improve the fit of the model to the data, indicating a lack of evidence that the group and view variables and their interaction influenced the likelihood of detecting the shifts of the images. These variables are ignored in further analyses.

The statistical test between the models described above, comparing full and reduced models, is referred to as a reduced model test. It was described in detail because it is used throughout the remainder of this report to test proposed hypotheses.

Influence of Shift Size on Detection

The experiment employed 3 shift sizes: 0.3, 0.6 and 1.2 deg. Because of unequal cell sizes a repeated measures, general linear model analysis was employed to test whether this variable influences detection frequency. A significant effect was obtained [F(2,17) = 3.97, p < .0004], and a post hoc test found that detection rates for all three conditions were significantly different (11%, 28% and 37% for the three conditions, Duncan Multiple-range Test, df=3, MSE = 0.0095). Thus, subjects are able to detect the shifts, and larger shifts are more detectable.

A second test of the effect of shift size on detection was conducted using the reduced model test. The data were partitioned into 3 sets corresponding to the three shift sizes, and equation (1) was fit to each separately. This yielded estimates of 6 parameters, an A and K parameter for each shift size, shown as Model B in Table 1. The loss values were summed for the three conditions, yielding an overall loss value of 571.971. Because Model A is a reduced version of Model B, the reduced model test was again

employed, showing that the 6-parameter, full Model B fit the data significantly better than the reduced, 2-parameter Model A [$X^2(4, N = 1339) = 95.822, p < .001$]. This result confirmed the fact that shift size affects the likelihood of detection.

The next test asked whether shift size actually affects only one of the two parameters being studied. It was hypothesized that increasing the shift size would elevate the function, increasing the intercept parameter, A, without changing its shape, indexed by the slope parameter, K. To test this hypothesis, two additional models were fit to the data: Model C, in which parameter K was held constant, and Model D, in which parameter A was held constant, while, in each case, letting the other parameter vary with shift size. The parameter estimates for these 4-parameter models are shown in Table 1. The loss value for constant slope Model C was 573.346 and for constant intercept Model D, 577.980. Both models were significant improvements over Model A [X^2 (2, $N = 1339$) = 83.324, $p < .0001$, X^2 (2, $N = 1339$) = 92.592, $p < .0001$]. The 6-parameter Model B was a significant improvement over the constant intercept Model D [X^2 (2, $N = 1339$) = 12.018, $p = .002$] but did not differ significantly from the constant slope Model C [X^2 (2, $N = 1339$) = 2.750, $p = .25$].

Because neither Model C nor Model D was a reduced version of the other, there is not an appropriate means of testing for a significant difference between them. However, because the constant slope Model C has a lower loss value than Model D, and is not significantly different from the 6-parameter Model B, it is accepted as equivalent to Model B and becomes the basis for further work. In accepting Model C, it is concluded that shift size affects the intercept of the saccade length function, and not its slope. The fit of Model C to the data from the three shift size conditions is shown in Figure 3, using the same sliding window method that was used for preparing Figure 2.

[Insert Figure 3 about here.]

Within Trial Serial Position Effects on Detection

In Experiment 1, the experimental pictures were each shifted twice during the 20 s viewing period, and these shifts could occur at different times during this period. This raises two questions. First, does the likelihood of detection change across the viewing period for a picture? And second, is there any difference in the likelihood of detection of the first vs. second picture shift.

Concerning the first question, researchers have often suggested that processing during the initial fixations on a picture is different from that occurring later: during initial eye fixations the general, low spatial frequency characteristics of the scene (global, holistic, or background features) are acquired, with greater detail being picked up during later fixations (Buswell, 1935; Loftus, Nelson, & Kallman, 1983). In addition, it is possible that, given the nature of the recognition task used, subjects might attend carefully to the picture during the first part of a viewing trial in order to store its characteristics (first viewing with the picture) or to determine whether anything had changed (second viewing), and then turn greater attention to the detection task during the latter part.

Concerning the second issue, because an initial shift of the picture was always followed 7 saccades later with an opposite shift of equal length (here called a *shift-back*), the occurrence of the first shift might prime sensitivity to the second. This could particularly occur if the internal response to the first shift was not large enough to lead to detection, but was large enough to sensitize the observer to the shift-back.

To test the hypothesis that detectability is greater to shift-backs than to shifts, the data were partitioned according to three variables: shift size (3 conditions), shift vs. shift-back (2 conditions), and serial position (6 positions: saccade 2, 9, 16, 23, 30 and 38). Crossing these variables yields 36 conditions, but only 30 actually exist: no shift-backs could occur on the 2nd saccade, and all changes on the 38th saccade

were shift-backs. Equation (1) was separately fit to data from each of these conditions, and the loss values summed across conditions. With 2 parameters per condition, this effectively created a 60-parameter model, Model E, which yielded a loss value of 533.184. A reduced model, Model F, was then constructed by eliminating the distinction between shift and shift-back, resulting in 18 conditions (3 shift sizes by 6 serial positions). Equation (1) was fit separately to the data of each of these conditions, and the loss values summed for a total of 546.447 for this 36-parameter model. The chi square test failed to show a significant difference between Models E and F [X^2 (24, N = 1339) = 26.526, p = .327]. Thus, the hypothesis that subjects are more sensitive to shift-backs than to shifts is not supported.

Turning next to the question of whether the likelihood of detecting a shift varies across the course of viewing a picture, the 36-parameter Model F was compared to Model B, the 6-parameter model that included only the shift size conditions and ignored serial position of the saccade on which the shift occurred. Thus, a test between Models B and F is a test of significance for serial position effects. This test yielded a significant difference [X^2 (30, N = 1339) = 51.048, p < .01], indicating the presence of serial position effects.

To test the hypothesis that this effect is due to processing differences during the initial fixations on a picture, a reduced version of the 36-parameter Model F was produced in which data for all serial positions greater than the 2nd saccade were collapsed into a single set for each shift size. This left only two values on the serial position factor, the 2nd saccade vs. other saccades, which, when crossed with shift size, resulted in a total of 6 conditions. Equation (1) was fit separately to data from each of these conditions and the summed loss value for this new model, Model G, with 12 parameters, was 560.536. Applying the reduced model test between the 36-parameter Model F and the 12-parameter Model G found no significant difference [X^2 (24, N = 1339) = 28.176, p = .253], nor does Model G differ significantly from the 60-parameter Model E [X^2 (48, N = 1339) = 54.702, p = .235]. Thus, collapsing the data across all serial positions following the 2nd saccade did not decrease the fit of the model significantly. On the other hand, a test between Model B, which did not include serial position effects, and Model G, which maintains the distinction between 2nd and later saccades, did produce a significant result [X^2 (6, N = 1339) = 95.506, p < .005]. This pattern of results indicates that the likelihood of detection is different for shifts that occur during the 2nd saccade than during later saccades. The likelihood of detection is quite low early in the viewing sequence. The A parameter estimates indicate the maximum level of detection for each condition: for the 0.3 deg condition, this reached only 5% for shifts occurring during the 2nd saccade in contrast to the 47% on later saccades.

In conclusion, detection is low on the initial fixations on a picture, but no further change in detection rate occurs across the sequence of later fixations. Thus, there is no evidence for increased sensitivity on change-backs, nor for greater attention to the secondary task later in the viewing period for a picture.

Influence of Relative Shift Direction

Previous investigators report that relative shift direction, the direction of a shift relative to the direction of the saccade during which it occurs, has no effect on the likelihood of detecting the shift. To determine whether a relation between these variables exists in the data from Experiment 1, two indices were created concerning the angular distance between the direction of a saccade and the direction of the shift that occurred during that saccade. First, the value of the internal angle between the direction of the saccade and the direction that the picture moved during the saccade, was calculated. This value, which ranges from 0 deg to 180 deg, served as the first relative shift direction index. The second relative shift direction index, ranging from 0 deg to 90 deg, was constructed by taking the value of the complementary angle of any angle greater than 90 deg. The first index would be related to detectability if it changes as the direction of image movement deviates from shift direction over a full 180 deg; the second index, if detectibility changes as the shift direction deviates from the line of saccade motion, ignoring direction, causing orthogonal motion to be either most or least detectable.

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Because the A parameter was influenced by shift size, it was hypothesized that this same parameter might also be affected by relative shift direction. Therefore, Model B, which assumed a constant value for the K parameter across shift sizes, was expanded by writing A as a linear function of relative shift direction, as shown in Equation (2):

(2) $$f(rsd,s) = (AI + AS * rsd) * e^{(K * s)}$$

In Equation (2), $f(rsd,s)$ is the likelihood of detection, AI is a parameter indicating the intercept of the linear function, AS is the slope of the linear function, K is a parameter controlling the rate of change with saccade length, rsd is the relative shift direction and s is the saccade length.

The data from Experiment 1 were partitioned into three sets, based on the shift size (0.3, 0.6 and 1.2 deg). Equation (2) was fit separately to each of these sets of data using the 180 deg relative shift direction index. Summing the resulting loss values yielded a total loss value of 541.103 for this 9-parameter model, Model H. Estimated parameter values are given in Table 1. Since Model B is a reduced version of Model H, including shift size differences but ignoring relative shift direction, the reduced model test was applied, yielding a significant difference [X^2 (3, N = 1339) = 61.736, $p < .005$]. Since the two models differ strictly in terms of whether relative shift direction is included, this result supports the hypothesis that relative shift direction affects shift detection. The parameter estimates in Table 1 show that the AS parameter is negative, indicating that detection likelihood decreases as relative shift direction increases; that is, with shift length and saccade direction held constant, shifts in the same direction as the saccade are more detectable than shifts in the opposite direction of the saccade.

A second test was made to determine whether the 90 deg relative saccade direction index is related to detectability. This was done in the same way as the application of Model H, except that the 90 deg relative shift direction index was used as the rsd variable. This model, Model I, produced a loss value of 556.755 which was also significantly different from Model B [$X2$ (3, N = 1330) = 30.432, $p < .005$]. Notice, however, that the loss value produced by the 180 deg index was substantially lower than that produced by the 90 deg index. This observation leads to the conclusion that the effect of relative shift direction is less related to the degree of orthogonality of the shift from the line along which the eyes move, than to the degree to which the shift direction deviates from the actual direction of the saccade.

An attempt was made to further simplify Model H by holding different parameters constant across shift size. Holding K constant produced a 7-parameter model, Model J, with loss value of 543.159 that is not significantly different from the 9-parameter Model H [X^2 (2, N = 1339) = 4.112, p = .128], again indicating that the variables are affecting the intercept rather than the slope of the basic saccade length function. Holding the AS parameter constant as well produced a 5-parameter model, Model K, with loss value of 560.556 that is significantly different from the 9-parameter Model H [X^2 (4, N = 1339) = 38.906, $p < .005$]. Model K, with the AS parameter constant, is also significantly different from the 7-parameter Model J in which the AS parameter varies with shift size [X^2 (2, N = 1339) = 34.794, $p < .005$]. These findings confirm that relative shift direction affects the intercept parameter, A, rather than the slope, K, of the saccade length function.

Discussion

The goal of Experiment 1 was to determine whether the likelihood of detecting intra-saccadic shifts of a naturalistic scene while examining it over time would show four characteristics observed with the detection of intra-saccadic shifts in much simpler displays. Only one of these characteristics was observed in the current data: the saccade length function (i.e., drop in the likelihood of detecting a shift as saccade length increases). In contrast, displacement threshold levels were much higher in the current study, as can be seen in Table 2 which compares current detection rates from Experiment 1, as estimated from the appropriate models, to those of prior studies having sufficiently overlapping

conditions. Detection rates in the present study were much lower than in previous studies that used very simple stimuli, but more similar to those of Bridgeman et al. (1975) who used the most complex stimulus pattern and relatively free viewing. The constant detection/saccade length ratio was not confirmed, as shown in Figure 4. And the current data did not show direction independence: rather, detection rate varied with relative saccade direction being greatest for shifts in the direction of the saccade, which is opposite the direction reported by Macknik et al. (1991). An interpretation for this result is given in the general discussion.

[Insert Table 2 and Figure 4 about here.]

In answer to the first question posed in the introduction of this report, it appears that findings from earlier studies with simpler stimuli do not generalize very well to a more naturalistic situation. Image shifts of sizes that can be detected under optimal conditions do not necessarily disrupt processing to an extent that they are noticed during normal viewing of complex scenes. This raises doubts about whether the earlier studies were investigating a fundamental mechanism by which visual stability is achieved in all visual perception, as cancellation theory would suggest. Rather, the fact that different situations not only change the level of detection, but even properties of the psychophysical functions themselves, is more consistent with theories that suggest that, while there is some basis for registering an intra-saccadic spatial displacement of the image, this does not necessarily disrupt on-going processing, and the degree to which the displacement is detected varies with the task and stimulus conditions. This is consistent with the observations of Matin et al. (1982) and Bridgeman and Graziano (1989) that the basis on which stimulus shifts are detected is different under illuminated conditions and with more complex stimuli than for simple stimuli in the dark.

The second question posed in the introduction concerns the functional stimulus region issue for detection of intra-saccadic shifts: is this detection based on a global assessment of stimulus position or direction, or only on some local information. This question cannot be addressed with data from Experiment 1, because local and global displacement properties are entirely confounded: the size of the displacement of the picture as a whole is the same as the size of the displacement of every object within the picture. Thus, a second experiment was conducted to investigate this second issue.

EXPERIMENT 2

To investigate the functional stimulus region issue for detecting stimulus shifts, and to test the target-object theory, it is necessary to create an intrasaccadic stimulus manipulation in which there is no unidirectional shift of the entire image, but the absolute position of objects in the region of the eyes' landing site varies. This was accomplished by expanding or contracting the picture from its center during selected saccades. With this manipulation, the image as a whole is not moved in any single direction, as it is when shifted, but the local objects do move, with direction and distance varying with position in the picture. There is little or no spatial displacement of objects near the center of the picture; magnitude of displacement increases with distance from the center, with direction of displacement determined by the direction of the object from the picture center. Thus, a *local displacement size* metric (*lds*) can be defined that is the distance that the eyes land from the point in the picture where they would have been had the image not changed size.

Detection of a change in the size of a picture might occur in any of three ways. First, detection might be based strictly on the local object displacements that result from changing the size of the picture, rather than on the size change itself. This will be called the *Displacement Only Hypothesis*. If this were the case, the likelihood of detecting a change would vary with local displacement size, and should be completely predictable by a generalization of the type of model developed for data in Experiment 1 with no additional effect of the magnitude of the size change. Second, it might actually be the size change itself that is detected, either perceiving a change in the size of the entire picture or some variable, such

as total luminance, that varies with it, or perceiving a change in the size of local objects within the picture. This will be called the *Size Only Hypothesis*. Because amount of change in size is constant across the picture, both locally and globally (that is, with a 10% increase the entire picture and every part of it increase by 10%), the likelihood of detecting a change would not vary with local displacement size but only with the magnitude of the size change itself. Third, detection might be based on some combination of these two types of information, which will be called the *Combination Hypothesis*. In this case, detection should vary with local displacement size in a manner that could be captured with the type of model developed for Experiment 1, but this model should require an additional parameter that varies with size change, independent of eye position within the picture. The goal of Experiment 2 was to determine which of these three hypotheses best account for detection of intrasaccadic changes in the size of a picture.

Method

The method used in Experiment 2 was identical to that in Experiment 1, with the data being acquired during the same picture viewings by the same subjects. A change in picture size was implemented by replacing the base picture, during one of the critical saccades, with an alternative version of the same picture that was either 10% or 20% larger or smaller, by volume, than the base version. Seven saccades later, the base picture was returned to the screen, producing a size change in the opposite direction of about the same amount. The base image was approximately 22 deg by 15 deg in size at the displayed distance, and the alternatives were approximately 24 x 17, 23 x 16, 21 x 14 and 20 x 13. The five versions were created by enlarging or shrinking the base image using the Truevision ATVista TIPS imaging software package v2.0. One change and change back was scheduled on each experimental picture, but whether these occurred depended on the number of saccades that were made. The four resulting size change conditions were counterbalanced across picture, critical saccade and picture sequence position in the same way as shift conditions were in Experiment 1. Subjects were not asked to determine what type of change occurred as they were viewing the pictures, but only to press their button if they detected a change of any type.

Two additional variables were attached to each saccade. The first, local displacement size (*lds*), indicates the absolute distance between the point in the picture where the eyes would have been directed had the picture size not changed, and the actual eye position. The second, relative displacement direction (*rdd*), indicates the angle in degrees, from 0 to 180, between the direction of the saccade and the direction of the local displacement.

Results

With 16 subjects, 32 experimental pictures, 2 presentations of each picture and 2 image size changes scheduled for each picture, there was a total of 2,048 changes possible; of these, good data, as defined in Experiment 1, were obtained from 1,543 changes, which were used in the following analyses.

For each subject, the percent of cases in which the display change was detected was computed for each of 8 conditions: the initial size change vs. the change back, and 4 different initial degrees of size change: large and small size increase, and large and small size decrease. A repeated measures analysis of variance on these data found a significant effect for size of change [$F(3,51) = 19.67, p < .0002$], but not for change vs. change back nor for any interaction. The detection rates for size change conditions are presented in Table 3, together with mean values for saccade length, local displacement size (*lds*), and relative displacement direction (*rdd*). As indicated earlier, the frequency of false alarms and late responses was very low, around 1%. Detection rates when the picture size was changed were much higher than these control condition rates, and differed significantly with condition with larger changes being associated with more frequent detection. The direction of the size change (expansion vs. contraction of the picture) had no effect on detection, a fact that was replicated in several attempts to

include this variable in models that are reported below, and so this variable is ignored in further analyses.

[Insert Table 3 about here.]

To test among the three alternate hypotheses stated above, a series of models was developed and fit to the data, similar to the exploration reported for Experiment 1. Parameter values are presented in Table 4. As a first step, three models were developed. Model L assumed that only size change affected detection: a single parameter varied with size change (10% or 20% change), producing a loss value of 957. A chi-square test rejected this model as an adequate description of the data [X^2 (1541, N = 1543) = 1914, p = < .0005]. Thus, a simple version of the Size Only Hypothesis is rejected.

Model M was created to determine whether the length of the saccade affects detection of changes in the size of a picture. It was identical to Model A of Experiment 1, fitting Equation (1) to the data. The loss value was 698, which was not rejected by chi-square test [X^2 (1541, N = 1543) = 1396, p = .997]. This result indicates that the detection of a change in the size of a picture, like the detection of a picture shift, is greatly affected by the length of the saccade during which the change occurred. Changes are detected more frequently when they occur during short saccades.

The third model uses the results of Model M to test whether the magnitude of the size change has an effect on its detection, once the effect of saccade length is taken into account. To do this, Model N was created by fitting Equation (1) separately to the two size change conditions, producing a 4-parameter model. The resulting loss value was 654, which is a significant improvement over Model M [X^2 (2, N = 1543) = 88, p < .0001]. This result indicates that both saccade length and the magnitude of the size change affect the likelihood of detecting the change.

Having established that the magnitude of the size change affects its detection, the issue addressed in the next set of models concerns whether this is due directly to the detection of the change in size itself, as represented by a more complex version of the Size Change Hypothesis which allows saccade length to also have an effect, or is due to the local displacement of eye position that is produced by the size change manipulation (Local Displacement Hypothesis). The first step in this process was to develop Equation (3) which makes detection likelihood a function of both saccade length and local displacement size (*lds*).

(3) $$f(lds,s) = (AI_i + AS_i * lds) * e^{(K * s)}$$

Because prior models have found that other variables primarily have their effect on the intercept of the detection function, Equation (3) makes the intercept a linear function of *lds*.[2] If the size of the local displacement is not having an effect on detection, then Equation (3) should fit the data no better than Equation (1).

To test for an effect of *lds*, two further models were created: Model O in which Equation (3) was applied to the total data set, collapsed across size change, and Model P in which Equation (3) was fit separately to data from the two size change conditions. Model O had a loss value of 682, and Model P, 645. The test of whether Equation (3), containing the *lds* variable, fits the data better than Equation (1), which does not, was accomplished in two steps. First, Model O was compared to Model M, and a significant difference was obtained [X^2(1, N = 1543) = 32, p < .0001]. Adding the *lds* parameter significantly improved the fit of the model. Second, Model N and Model P were compared. Model N applies Equation (1) to the data from the two size changes separately, and Model P does the same for Equation (3). Thus, this comparison tested the question of whether, after taking size change into account, adding the *lds* parameter still improves the fit of the model. A significant difference was again found [X^2 (2, N = 1543) = 88, p < .0001] with Model P fitting the data better. Thus, the local

displacement size has an effect on detection likelihood, over and above any effect of size change itself. This effectively rules out the Size Change Only Hypothesis.

A choice between the Local Displacement Only Hypothesis and the Combination Hypothesis can be made by examining the loss values of Models N and O. If the effect of size change on detection were entirely due to the local displacements that are produced, as the Local Displacement Only Hypothesis assumes, then the fit of Model O should be at least as good as that of Model N. Having the *lds* parameter in Model O, which does not distinguish between size change conditions, should allow it to fit the data at least as well as Model N, which takes size change into account directly but has no *lds* parameter. This prediction is not supported by the data: the loss value for Model O is much higher than that for Model N, thus failing to support the Local Displacement Only Hypothesis. Thus, size change is producing an effect on detection likelihood beyond effects of saccade length and local displacement size.

If size change is producing an independent effect, this suggests that a model in which the effect of size change is represented by a separate parameter should give a more adequate description of the data. Equation (4) captures this assumption by adding a size change parameter, C_{sc}, to Equation (1), where the C parameter varies as a function of size change, *sc*.

(4) $$f(s,sc) = A * e^{(K*s)} + C_{sc}$$

Model Q consists of fitting Equation (4) to the data from Experiment 2, thus having 4 parameters, A, K and two values of C, one for the 10% change and one for 20% change data. A and K are assumed not to vary with size change. The loss value for Model Q is 636, which is significantly lower than that of Model M [X^2 (2, N = 1543) = 124, $p < .0001$]. It is also much lower than the loss value for Model N, which has the same number of parameters, but which attempts to capture the difference between size change conditions by varying the A and K parameters. Thus, there is an effect of size change that is best represented by a separate parameter.

Given that Model Q gives a more adequate representation of the effect of size change on detection, it is necessary to determine whether local displacement size still affects detection. This was done by creating Equation (5), which makes the intercept parameter, A, from Equation (4) a linear function of *lds*.

(5) $$f(s,sc,lds) = (AI_i + AS_i * lds) * e^{(K*s)} + C_{sc}$$

Model R consisted of fitting Equation (5) to the data, thus producing a 5-parameter model, and yielding a loss value of 631, which is a significant improvement over Model Q [X^2 (1, N = 1543) = 10, $p < .002$]. Thus, local displacement size is still found to produce an effect on detection, further ruling out the Size Change Only Hypothesis. The fact that contrary evidence has been found for both the Size Change Only and Local Displacement Only Hypotheses leads to the acceptance of the Combination Hypothesis: both local displacement size and magnitude of size change are affecting detection likelihood.

A further model tested whether relative displace direction, *rdd*, produces an additional effect on detection, as it did in Experiment 1. Model S was created by replacing the AI_i parameter in Equation 5 with a linear function of *rdd*. This did not significantly improve the fit of the model, as compared to Model R [loss value = 630, [X^2 (1, N = 1543) = 0.8, $p < .371$]. Thus, there is no evidence that relative displacement direction influences the frequency of detecting the picture size changes in Experiment 2.

In Equation (5), Model R, the estimates for parameters C_{10} and C_{20} directly indicate the size of the increment in detection likelihood due to size change after the effects of saccade length and local displacement size are taken into account. As Table 4 indicates, the estimates for these parameters are

0.024 and 0.160. The size of the increment for 10% size changes is very small, which raises the question of whether this is a statistically significant increment. This question was tested by modifying Model R to force the $C^{10} = 0$, producing Model T having 4 parameters. The loss value for Model T is 650, which is a significantly poorer fit than that for Model R [X^2 (1, N = 1543) = 39.8, $p < .0001$]. This finding leads to the conclusion that even the 10% size change is being detected directly to some degree, beyond detection based on local displacements.

Discussion

Experiment 2 was conducted to determine whether the detection of intrasaccadic shifts of pictures, studied in Experiment 1, is based on local displacements of eye position within the pictures. The results indicate that the size of the local displacement does provide a signal on which detection of intrasaccadic change is based, but that, in addition, change in picture size itself makes a unique contribution to this detection, as suggested by the Combination Hypothesis. This result is evidence that at least part of the picture shift detection in Experiment 1 was based on local displacement size, rather than on a detection of the global displacement of the picture as a whole.

The finding that the size of the local displacement affects detection raises a final question concerning whether this was the only basis for shift detection in Experiment 1, or whether detection was based both on this factor and some more global perception of the displacement of the picture as a whole. To test for the detection of picture shifts based on global stimulus characteristics, a final pair of models was developed and fit simultaneously to data from Experiments 1 and 2. The data consisted of a 6-tuple for each critical saccade in which the image was either shifted or changed in size. The 6-tuple consisted of (1) whether the change was detected (the dependent variable); (2) the saccade size, *s*; (3) the local displacement size, *lds*, which, in the case of Experiment 1, consisted of the shift size; (4) the relative displacement direction, *rdd*, similar to relative shift direction in Experiment 1; (5) the global shift size, *gss*, which had a value equal to the shift size for data from Experiment 1 and a value of zero for data from Experiment 2; and (6) the global size change, *sc*, which had a value of the size change for data from Experiment 2 and a value of zero for data from Experiment 1. The first model, Model U, was constructed by combining Equations (2) and (3) to make the intercept an additive function of both *lds* and *rdd*, and adding terms for global shift size and size change, as shown in Equation (6):

$$(6) \qquad f(s,sc,lds,rdd,gss) = (AI + ASL * lds + ASR * rdd) * e^{(K * s)} + C_{sc} + G_{gss}$$

This model assumes that there is a common factor that contributes to detection likelihood in both experiments, namely, local displacement size and direction. In addition, there is a unique factor in Experiment 2, global size change, and another unique factor in Experiment 1, global shift size.

With 2 size changes and 3 global shift sizes, Model U has a total of 9 parameters. A reduced model, Model V, was formed by deleting the G parameter. Testing the difference between the fit of these two models constitutes a test for whether the size of picture shifts in Experiment 1 influenced detection likelihood in a manner not captured by local displacement size. A significant difference between these two models would serve as evidence that a global influence of shift size is producing an effect on the likelihood of detecting the intrasaccadic changes, above and beyond that resulting from the local displacements of the eyes' landing position that results.

Loss values for Models U and V were 1257 and 1271, successively, which are significantly different [X^2(3, N = 3033)= 28.4, $p < .0001$]. This difference leads to the conclusion that the detection of shift size is not based entirely upon local displacement size, indicating the presence of a more global effect, as well. Estimated parameter values are presented in Table 5.

GENERAL DISCUSSION

Two experiments were performed to study the phenomenon of space constancy or visual stability, the tendency to perceive the world as stable even though its position is displaced on the retinae with every saccadic eye movement. The studies focused on two issues that arise from a review of current theories of visual stability: whether results from earlier studies involving the detection of intrasaccadic shifts of simple stimuli in the dark generalize to a more naturalistic stimulus and task, and whether shifts in the stimuli are detected on the basis of local information in the region of the saccade's landing position, or on the basis of more global information about the position of the image as a whole. A visual world was created with naturalistic, full-color images on a computer screen, in which the pictures being examined occasionally changed position (shifted) or changed size during saccades as the observers were examining the pictures either to remember them or to determine whether they were the same as in an earlier viewing. The observers indicated when they detected a change, thus noting a violation of visual stability. Experiment 1 investigated the issue of generalizability of results. Of the four primary results from earlier research, only one, the tendency for detection to drop as saccade length increases, was replicated here. The other three results did not generalize: displacement thresholds were much higher in the naturalistic situation than in earlier studies, there was not a constant ratio between detection likelihood and saccade length as saccade length varied, and it was not true that the shift direction, relative to the saccade direction, had no effect. Rather, shifts that went in the direction of the saccade were detected more frequently than shifts in the opposite direction, though this result was not replicated with the smaller local shifts in Experiment 2. Thus, it is concluded that detection frequency and its relationship to other variables is not constant across stimulus and task conditions.

Experiment 2 addressed the issue of whether the detection of image shifts is based on local vs. more global information. The results indicate that detection of intrasaccadic changes in the size of pictures is a function of the local displacement size, or how far the eyes land from the picture location where they would normally have landed had the change not occurred. This is taken as evidence for detection based to a large extent on local information, namely, where the eyes land with respect to their target. Evidence was also found for the direct detection of size change, though the study did not permit distinguishing between whether this was based on local information, such as the change in size of, or in distance between, objects in the region of the eyes' landing position, or global information, the overall change in size of the picture.

In a final attempt to simultaneously model data from both experiments, the model did not account for all of the effect of shift size on detection observed in Experiment 1. This indicates either an inadequacy in the model or that some factor other than local displacement size also contributes to the detection of the shifts in that experiment. These possibilities require further investigation.

The observations above have implications for each of the four types of theories of visual stability outlined in the introduction. The fact that observers detect intrasaccadic shifts in pictures, even when this is not their primary task, once again argues against Gibson's (1966) account of visual stability as being the result of properties of the proximal stimulus alone: rigid, discrete retinal displacements during periods of saccadic suppression. The image shifts used in Experiment 1 largely met that criterion, yet were detected about as well as the size changes occurring in Experiment 2, which did not. One qualification on this conclusion results from the fact that, although the pictures appeared on a large, dark surface and in semi-darkness, there were two aspects of the visual field that did not shift when a picture shifted, thus resulting in a lack of a completely rigid transformation from fixation to fixation: dim patterns in the far periphery, and part of the eyetracking equipment itself which was visible. Still, the fact that other investigators, working in complete darkness, have found intrasaccadic stimulus shifts that constitute rigid transformations to be detected argues against a strictly stimulus-based explanation of visual stability.

The current results are compatible with other recent observations that the perception of stability is different with complex stimulus patterns than with simple patterns in the dark (Bridgeman & Graziano, 1989). This suggests that the mechanism postulated by cancellation theory, and studied in many earlier experiments, is either not fundamental to the maintenance of visual stability in normal viewing, or that the signal produced by across-saccadic image misalignment plays a decreasing role in vision as image complexity increases. In the current study, it can be further argued that the signal produced by misalignment is less likely to be noticed when its detection is not the observer's primary task, thus accounting for the low detection levels relative to those found in previous experiments. However, taking this position raises serious questions about how fundamental the cancellation process really is in maintaining visual stability: apparently, normal perceptual processing can proceed smoothly in the face of stimulus displacements that are much larger than those that can be detected with simple stimuli in the dark.

Finally, the current results indicate a need for cancellation theory to be revised to give priority to the alignment of local information in the region of the eyes' landing position following a saccade.

Postulating a process that does not cancel out discrepancies between the retinal locations of the stimulus pattern between fixations, but that provides a signal concerning the extent to which the image on one fixation is at the location where it would be expected, given the intervening saccade, leads naturally to the third type of theory. MacKay's (1973) "cognitive approach," and Bridgeman et al.'s (1994) "taking into account" theory, suggest that various types of information are evaluated in determining whether a change has occurred in the stimulus. Unless evidence is present suggesting otherwise, the visual system assumes that the world has remained stable from one fixation to the next. This type of theory seems to accommodate the results from Experiments 1 and 2 most easily, because the information examined and the nature of the tests made could vary with stimulus and task characteristics. Thus, differences in detection frequency and psychophysical functions across tasks are to be expected, and greater consideration could be given to information near the eyes' landing position than to the global stimulus pattern. The primary problem with this type of theory is that it lacks specificity; the nature of the mechanism that takes information into account, the nature of the information used, and the rules of operation have not yet been specified sufficiently well to permit strong tests of the approach. In particular, it is not clear what the information and mechanism might be that detects intrasaccadic shifts of pictures. In this case, the interpretation given to the picture, the objects contained in it and the spatial relations among them, remain invariant, thus providing no indication of stimulus change. The only thing that is changed is the spatial relation between the observer and the stimulus. Thus, Bridgeman et al. (1994) propose that, on each fixation, a calculation is made concerning the "direction of the world." This vector can be compared from fixation to fixation, and a discrepancy in direction is detected if it is sufficiently large.

Irwin, McConkie, Carlson-Radvansky, and Currie (1994) have criticized Bridgeman et al.'s explanation of detecting stimulus shifts by pointing out that the world, in fact, has no direction; only objects or regions have direction with respect to the observer. Furthermore, each object or region has a different direction. This raises the question of whether the visual system calculates a direction for each, or for a subset of, objects or regions, and then detects shifts on the basis of changes in all or some of these directions. In particular, the finding that local discrepancies in landing positions predict shift detection suggests that the direction of the object to which the eyes are being sent may play a key role in detecting stimulus shifts.

Closely related to the interpretation of taking-into-account theory is the fourth type of theory discussed above, the saccade target theory, which postulates that a shift of the stimulus is detected on the basis of the post-saccadic retinal location of the object to which the eyes are sent. This theory appears to overcome the limitations of the Bridgeman et al. proposal and to be quite compatible with many of the current results. Because this type of mechanism has only been alluded to indirectly in previous literature

(Bridgeman & Stark, 1979), an elaboration of it is attempted here. It is referred to as the *saccade target theory of visual stability* (Irwin et al., 1994).

The proposed theory makes the following basic assumptions:

Assumption 1. The visual system assumes that the world remains consistent during the period of a saccade (Bridgeman et al., 1994; MacKay, 1973). This assumption is accepted unless there is disconfirmatory evidence. Of course, a key issueconcerns the nature of such evidence and how it becomes available.

Assumption 2. There is no carry-over of the retinal image from the end of one eye fixation to the beginning of the next (Irwin, 1991; O'Regan, 1992; Pollatsek & Rayner, 1992). Hence, there is no integration of successive images, as Breitmeyer et al., (1982) and others have assumed. The only information that survives a saccade is that which has been specifically selected for encoding and storage in a more abstract form. From an evolutionary perspective, there is no need for an organism to have a memory for the full complexity of the visual stimulus, since the full set of information is contained within the world itself and is continuously projected to the retina of the observer whose eyes are open (O'Regan, 1992).

Assumption 3. There exists a mental representation of selected information from the scene being viewed, which includes information about the properties and locations of objects and regions within the scene that have been previously attended, as well as more global information about the nature, structure and characteristics of the scene as a whole. The nature of this representation is, of course, much in dispute.

Assumption 4. The early visual processes parse a complex stimulus configuration into a hierarchical structure of regions, together with their features or properties, that will be referred to as an *object hierarchy* (Palmer, 1977).

Assumption 5. On each eye fixation, a *mapping function* is established between the stimulus configuration provided by the retina, and the mental representation. This mapping function makes it possible, from any region in either of these two spaces, to locate the corresponding region in the other upon request.

Assumption 6. Each saccade is normally an attempt to direct the eyes toward some selected entity in the retinally provided stimulus structure, thus bringing it onto a part of the fovea that provides higher spatial resolution. The selected entity will be referred to as the *target object*.

With these basic assumptions about visual perception, we now propose a mechanism by which stimulus displacements may be detected.

Step 1. During each eye fixation, a target object (see Assumption 6) is selected from the retinally provided object hierarchy as the goal of the following saccade. While the process by which this selection is made is of great interest, it will not be dealt with further at this time.

Step 2. The location of the saccade target in the mental representation is noted.

Step 3. Certain features or information about the target object are selected and stored, in order to facilitate its identification at the onset of the following fixation. This is referred to as the *locating information*. The nature of the locating information, and whether it varies by task, stimulus, or eccentricity of the saccade target, are issues that require further research.

Step 4. A saccade is initiated to bring the target object into central vision. The accuracy of the saccade can be compromised by various influences such as the global effect (Findlay, 1982), range effect (Kapoula, 1985) and perceptual inaccuracy (Coëffé & O'Regan, 1987).

Step 5. As new visual information begins to become available following the saccade, a fast, probably parallel, search is made in an attempt to find the locating information that indicates the retinal location of the saccade target. This scan is made within a limited region, referred to as the *saccade target search region*, probably determined by past experience with the distribution of retinal locations of saccade targets. We will refer to this as the *saccade target locating process*.

Step 6. When the saccade target is located in the stimulus array, the relationship between its retinal location and the previously noted location (see Step 2) in the mental representation is identified. This gives rise to a bi-directional mapping function between these two spaces. Given a location in either space, the approximate corresponding location in the other space is specified. Thus, this function is the basis for identifying the appropriate location in the mental representation for information obtained from a stimulus object or region, and for identifying where in the retinally provided stimulus array attention should be directed to obtain further information about some object or region already included in the mental representation.

Step 7. Having established the mapping relationship between retinal space and the mental representation, normal perceptual activity (i.e., acquiring and using visually-provided information for the task at hand) is able to proceed normally during that fixation.

By the saccade target theory, the sense of a stable visual world occurs when the locating process is successful; that is, when, at the onset of each fixation, the saccade target is found within the initial search region. It is postulated that a failure of the saccade target locating process is evidence for instability in the stimulus array, contradicting the assumption of a stable visual world. When the image is shifted during a saccade, this increases the likelihood that the saccade target will not lie within the search region, thus increasing the likelihood that the locating process will not succeed. When the locating process initially fails, a wider search must be initiated in an attempt to find the target. Normal perception proceeds only when the target is found, or it is concluded that it no longer exists and processing must continue on some other basis.

The saccade target theory provides explanations for several of the observations from Experiments 1 and 2. First, the conclusion that image shifts are detected on the basis of local information is consistent with this theory, which depends specifically on the saccade target locating process to maintain visual stability, rather than on any sort of global image integration across saccades. Second, larger image shifts are more likely to be detected because they are more likely to move the saccade target out of the search area for the following fixation. Third, image shift detection drops with longer saccades because, since the distribution of landing sites following longer saccades is more variable (McConkie, Kerr, Reddix, & Zola, 1988), a larger search region is probably employed under these conditions. The larger search region reduces the likelihood that a shift of a given size will take the target outside the region, thus reducing the likelihood of detecting the shift. It should also be noted that in viewing naturalistic scenes like those used in the above experiments, longer saccades are, on the average, probably taking the eyes to larger saccade targets, and larger targets are less likely to move out of the search region with a shift of a given size. Fourth, if target object size is a factor in the frequency of detecting stimulus shifts, this could explain why detection is so much poorer for shifts made early in the viewing of a picture. During the first few fixations, the observer probably attends broadly to the picture, identifying its theme and general structure; during this process, the eyes are sent to the largest objects and regions in the picture, resulting in reduced likelihood that a target object will lie outside the search region. During later fixations, as smaller objects and details are attended, the frequency of shift detection is increased. Fifth, the fact that shifting the image in the same direction as the saccade results in higher detection than

shifting opposite that direction results from a characteristic of saccadic movements: when making saccades to a target, there is a tendency to undershoot that target, though the actual error is dependent upon the launch site of the saccade, as well (Kapoula, 1985). Thus, on average, shifting the image in the direction of the saccade would have a tendency to exacerbate such an undershoot, whereas shifting the image opposite the direction of the saccade will often reduce this type of error. Assuming that there is a tendency for the search region to be biased toward the center of the fovea, this would result in a greater likelihood of the saccade target lying outside the search region, and, hence, of detecting the shift, when the image is shifted in the direction of the saccade than when it is shifted against that direction. This is the pattern observed in Experiment 1. The fact that no effect of relative displacement direction was found in Experiment 2 could be due to the smaller displacements involved in that study.

Finally, while a failure in the locating process is one indication of instability in the stimulus world, other indications can also exist. First, the saccade target model did not succeed in accounting for the entire shift size effect in Experiment 1. It is not clear at this point whether this result is due to inadequacies in the formalism of the model developed in this paper (e.g., using non-optimal functions, or not including critical interaction terms in the model), or to the existence of a true, non-local image displacement effect. Further investigation and modeling will be required to resolve this issue. If a non-local effect is indeed documented, as suggested by the present study, it will be necessary to investigate its nature, and particularly to determine whether it has properties expected by a form of cancellation theory.

Second, Experiment 2 found that changes in the size of the image contribute to detection, independent of the accompanying local shift in the image. However, this experiment did not provide appropriate data for identifying the basis on which this detection occurred. Some possible bases for detection that must be investigated in future studies include the following: a change in the total illumination from the picture, a change in the global size of the illuminated region of the picture, a change in the size of the saccade target, or a change in the distance of the saccade target from nearby objects.

Future work is also needed to identify other sources of evidence for instability in the stimulus configuration from one fixation to the next. As a conceptual framework for this work, we suggest the following bases for the detection of change between fixations: (a) failure to locate the saccade target, which can result either from its not being in the search area, or from a change in the locating information; (b) an abrupt change in certain low-level perceptual characteristics of the stimulus field, such as total luminance, brightness, or dominant hue, which may disturb the system, perhaps even during the saccade itself; (c) change in properties of some object or region of the stimulus field that has been previously coded and included in the mental representation, other than the locating information, so a recoding of that information leads to a discrepancy between newly-acquired and previously represented information. It should be noted that these three bases for detection of change would be expected to occur at quite different levels of processing, and hence at different times following the onset of an eye fixation. Whereas failure to locate the saccade target and changes in low-level perceptual characteristics should be noted early in the fixation, changes in a previously coded object should only be noticed later when information from that object is specifically attended and brought into contact with its previously stored representation. A possible procedure for distinguishing among such different sources of effects by comparing frequency distributions of fixation durations has been suggested by McConkie, Reddix, and Zola (1992).

The saccade target theory of visual stability, as stated above, does not postulate a role for a corollary discharge signal in achieving visual stability. Future work is needed to address the issue of whether this type of theory can account for results from studies involving the detection of intrasaccadic displacements of simple stimuli in the dark, or whether under these conditions a corollary discharge signal must be assumed as suggested by recent work by Bridgeman and his associates (Bridgeman & Graziano, 1989; Bridgeman & Stark, 1991).

There are two limitations of these experiments that should be noted. First, all conclusions come from data pooled across subjects, and single subject replication is needed. Second, it is possible that subjects are less sensitive to changes in raster-refreshed computer displays, such as those used in the present experiments, than they are to steady displays (Kennedy & Murray, 1991).

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Footnotes

[1]It should be noted that except in highly controlled circumstances, the change in the pattern of light on the retina that results from making a saccade is not identical to that produced by shifting a two-dimensional image the same distance in the opposite direction. However, the small differences that might result, given the circumstances of the experiments reported below, will be ignored in this report.

[2]As an alternative to Equation (3), a model was also created in which k, rather than A, was written as a function of *lds*. This model yielded a loss value of 678.13, which is significantly better than that from Model M [$X^2(1, N = 1543) = 39.04, p < .0001$]. This model fit the data slightly better than Model O. Because these are not nested models, there is no good method of statistically testing whether they differ, but they are so close that it is unlikely that the obtained difference is reliable. Because in prior models, having variables affect the intercept parameter led to better fitting models, we chose to continue the analysis based on Equation (3), rather than on this alternative equation.

[3]The Saccade Target Theory of Visual Stability was first presented by the first author at the 6th European Conference on Eye Movements, Leuven, Belgium, in September 1991, in a paper entitled "Perceiving a Stable Visual World."

Table 1

Models Tested in Experiment 1

Model	A Parameters (Intercept)	K Parameters (Slope)	No. Params	Loss	Tests
A	Base Model (Equation 1)				
	A 0.863	K -.591	2	620	
A	Base model fit separately to each Group by View subset of data (Equation 1)				
	A 0.685 to 1.096	K -0.473 to -0.890	16	611	A
Effect of Shift Size					
B	Base Model (Eq 1) fit separately to each Shift size				
	$A_{0.3}$ 0.383	$K_{0.3}$ -0.698	6	572	A*
	$A_{0.6}$ 0.922	$K_{0.6}$ -0.621			
	$A_{1.2}$ 1.141	$K_{1.2}$ -0.518			
C	Base Model (Eq 1) modified: Shift size affects intercept only				
	$A_{0.3}$ 0.332	K -0.581	4	573	B
	$A_{0.6}$ 0.894				
	$A_{1.2}$ 1.194				
D	Base Model (Eq 1) modified: Shift size affects slope only				
	A 0.912	$K_{0.3}$ -1.310	4	578	B*
		$K_{0.6}$ -0.614			
		$K_{1.2}$ -0.411			

Table 1 (Continued)

Model	A Parameters (Intercept)	K Parameters (Slope)	No. Params	Loss	Tests
Effect of Shift/Shiftback and Serial Position					
E	Base Model (Eq 1) fit separately to each Shift/shift-back by Serial position subset of data				
			60	533	B*
F	Base Model (Eq 1) fit separately to each Serial Position		36	546	E,F*,B*
G	Base Model (Eq 1) fit separately to each Serial Position		12	561	E,F,B*
Effect of Shift Direction					
H	Relative Shift Direction (180 deg) included in model (Eq 2)				
	$AI_{0.3}$ 0.759 $AS_{0.3}$ -0.004	$K_{0.3}$ -0.711	9	541	B*
	$AI_{0.6}$ 1.001 $AS_{0.6}$ -0.003	$K_{0.6}$ -0.506			
	$AI_{1.2}$ 1.713 $AS_{1.2}$ -0.005	$K_{1.2}$ -0.493			
I	Relative Shift Direction (90 deg) included in model (Eq 2)		9	557	B*
J	Intercept as function of Relative Shift Direction (180 deg) (Eq 2)				
	$AI_{0.3}$ 0.661 $AS_{0.3}$ -0.004	$K_{0.3}$ -0.573	7	543	H
	$AI_{0.6}$ 1.249 $AS_{0.6}$ -0.005				
	$AI_{1.2}$ 1.764 $AS_{1.2}$ -0.006				
K	Only intercept is function of Relative Shift Direction (180 deg) (Eq 2)				
	$AI_{0.3}$ 0.933 $AS_{0.3}$ -0.005	$K_{0.3}$ -0.591	5	560	H*,J*
	$AI_{0.6}$ 1.100				
	$AI_{1.2}$ 1.785				

*Statistically significant difference between models using the reduced model test. Codes only indicate tests against earlier models.

Table 2

Between-Study Comparisons of Average Detection Rates (Detect) as a Function of Saccade Length (SacLen) and Shift Size (ShftS)

	Prior Study			Experiment 1		
	SacLen	ShftS	Detect	SacLen	ShftS	Detect[a]
Li & Matin (1990)	4°-7°	0.5°	60%	4°-7°	0.45°[b]	9%
Whipple & Wallach (1978)	7°	0.7°	80%	7°	0.6°	0%
Li & Matin (1990)	4°-7°	1.5°	60%	4°-7°	1.2°	12%
Mack (1970)	3°	0.6°	50%	3°	0.6°	15%
Bridgeman, Hendry, & Stark (1975)	3°-5°	1°	0%	4°	1°	12%

Note:

[a]These values are derived from the exponential functions in Figure 2.

[b]This is an average of the 0.3° and 0.6° shift size condition.

Table 3

Likelihood of Detecting Changes in Picture Size (Detect), Together With Mean Local Displacement Size (lds) Saccade Length (sl) and Relative Displacement Direction (rdd)

		Average Values			
Picture Change		lds	sl	rdd	Detect
10% Increase	*M*	0.25°	3.00°	60.77°	.253
	(*SD*)	(0.15°)	(2.78°)	(52.26°)	
10% Decrease	*M*	0.24°	2.99°	61.27°	.238
	(*SD*)	(0.14°)	(2.57°)	(52.81°)	
20% Increase	*M*	0.45°	3.03°	68.07°	.469
	(*SD*)	(0.29°)	(2.91°)	(55.17°)	
20% Decrease	*M*	0.49°	3.40°	60.16°	.431
	(*SD*)	(0.34°)	3.10°)	(53.22°)	

Table 4

Models Tested in Experiment 2

Model	A Parameters	K Parameters	SC Parameters	No. Params	Loss	Tests
L	Size Change only		SC_{10} 0.245	2	960	
			SC_{20} 0.507			
M	Base Model fit to size change data (Eq1)					
	A 1.030	K -.542		2	698	
N	Base Model fit separately to two Size Change data sets (Eq 1)					
	A_{10} 0.985	K_{10} -.733		4	654	M*
	A_{20} 1.216	K_{20} -.474				
O	Make A a function of Ids (local displacement size) (Eq 3)					
	AI 0.880 ASds 0.460	K -0.547		3	682	M*
P	Apply Model O to Size Change conditions separately (Eq 3)					
	AI_{10} 0.907 $ASds_{10}$ 0.280	K_{10} -0.727		6	645	N*
	AI_{20} 1.106 $ASds_{20}$ 0.143	K_{20} -0.457				
Q	Base Model plus Size Change (Eq 4)					
	A 1.034	K -.837	SC_{10} 0.023	4	636	M*
			SC_{20} 0.182			
R	Base Model plus Size Change (Eq 5)					
	AI 0.928 ASds 0.347	K -.828	SC_{10} 0.023	4	631	Q*
			SC_{20} 0.162			

Table 4 (Continued)

Model	A Parameters	K Parameters	SC Parameters	No. Params	Loss	Tests
S	Base Model, lds, rdd, & Size Change (Eq 5)					
	AI 0.922 ASds 0.302 ASrd 0.0004	K -.837	SC_{10} 0.024	6	630	R
			SC_{20} 0.160			
T	Base Model, lds, rdd, & Size Change 20% only (Eq 5)					
	AI 0.941 ASds 0.284 ASrd 0.0002	K -.687	SC_{10} set to 0	5	650	R*
			SC_{20} 0.116			

*Statistically significant difference between models

Table 5

Models Involving Data from Both Experiments 1 and 2

Model	A Parameter		K Parameter	Global Parameters		No. Params	Loss	Tests
	Intercept	Slope		C(Size Chng)	G(Shift size)			
U	Model including global parameters for Size Change (C) and Shift Size (G) (Eq 6)							
	AI 0.951	ASL 0.423	K -0.799	C_{10} .033	$G_{0.3}$ .005	9	1257	
		ASR -0.002		C_{20} .192	$G_{0.6}$ .013			
					$G_{1.2}$ .083			
V	Model including global parameters for Size Change (C) but not Shift Size (Eq 6)							
	AI 0.880	ASL 0.526	K -0.799	C_{10} .026		6	1271	U*
		ASR -0.002		C_{20} .163				

*Statistically significant difference between models.

Figure Captions

Figure 1. Schematic example of the sequence of changes taking place in a picture during the 20 sec viewing period. Each change occurs during the indicated saccade.

Figure 2. Relationship between saccade length (s) and proportion of detections of intrasaccade shifts of the picture (f(s)). Each proportion and mean saccade length is based on 100 cases (see text).

Figure 3. Relation between saccade length (s) and proportion of detections of intrasaccadic shifts of the picture (f(s)), for shifts of different distances. Each proportion and mean saccade length is based on 100 cases (see text).

Figure 4. Shift magnitudes that result in three constant detection rates for three saccade lengths, as estimated from Model K. If detection were a constant function of the ratio of shift magnitude to saccade length, these curves would be linear.

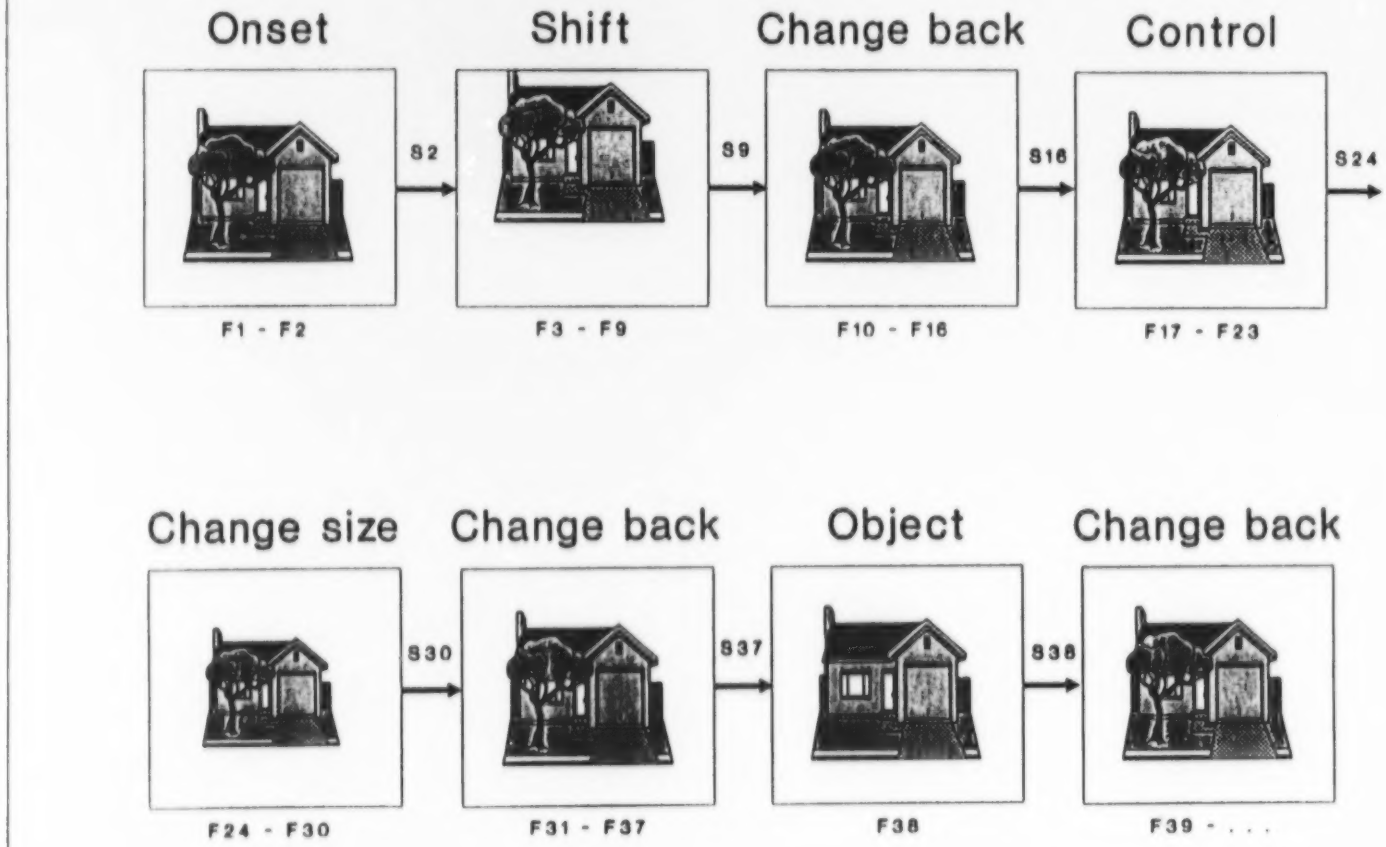
Onset
Shift
Change back
Control
S2
S9
S16
S24
F1 - F2
F3 - F9
F10 - F16
F17 - F23
Change size
Change back
Object
Change back
S30
S37
S38
F24 - F30
F31 - F37
F38
F39 - . . .

Figure 1

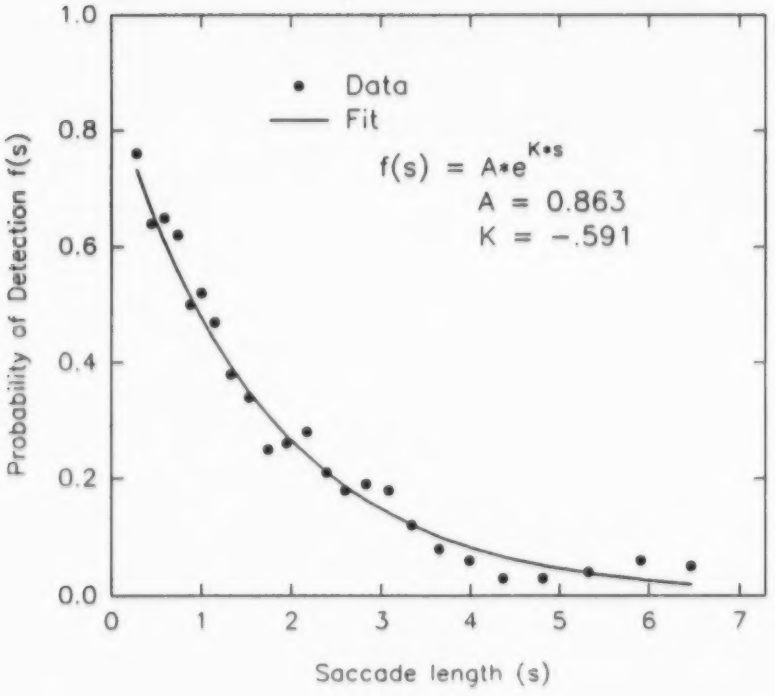
Data
Fit
f(s) = A•e^K•s
A = 0.863
K = −.591
Probability of Detection f(s)
Saccade length (s)
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7

Figure 2

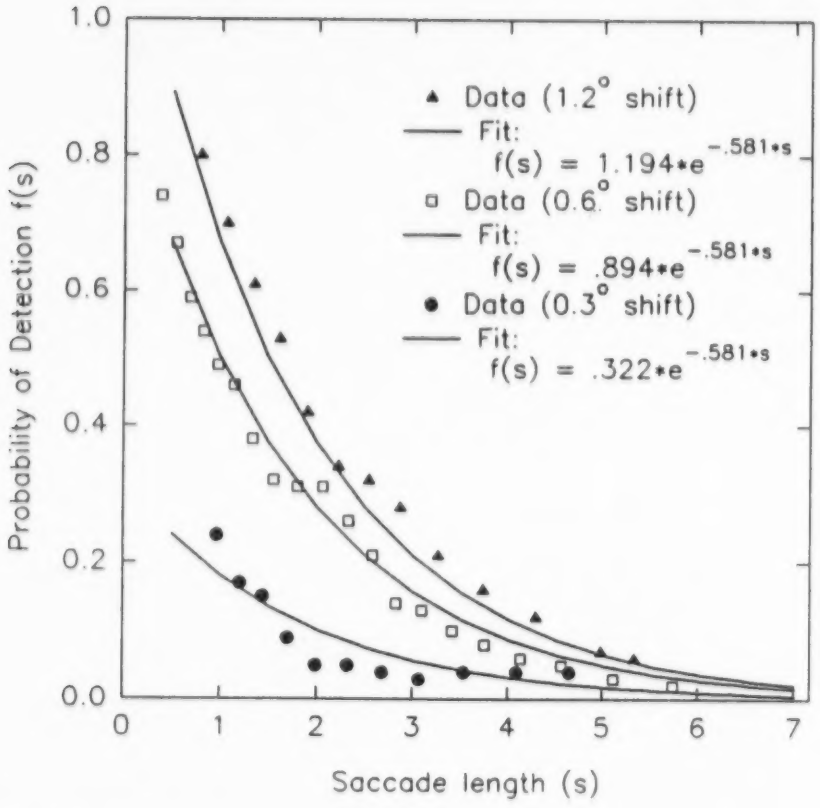
1.0
0.8
0.6
0.4
0.2
0.0
Probability of Detection f(s)
0
1
2
3
4
5
6
7
Saccade length (s)
Data (1.2° shift)
Fit:
f(s) = 1.194*e^-.581*s
Data (0.6° shift)
Fit:
f(s) = .894*e^-.581*s
Data (0.3° shift)
Fit:
f(s) = .322*e^-.581*s

Figure 3

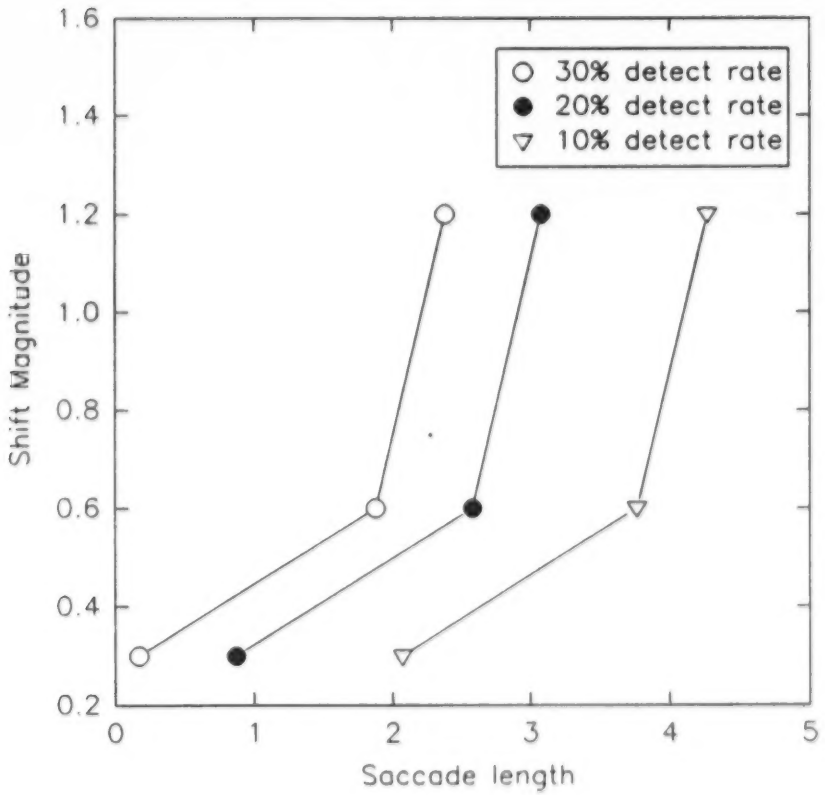
30% detect rate
20% detect rate
10% detect rate
Shift Magnitude
Saccade length
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
5

Figure 4